Top quark physics expectations at the LHC

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The top quark will be produced copiously at the LHC. This will make possible detailed physics studies, and also the use of top quark decays for detector calibration. This talk reviews plans and prospects for top physics activities in ATLAS and CMS experiments.

1. Introduction

ATLAS and CMS are general purpose detectors at the LHC, which will provide proton-proton collisions with center of mass energy 14TeV and instantaneous luminosity up to $L = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Compared to the Tevatron, the production cross section at the LHC is expected to be two orders of magnitude larger for top quark pairs, but only an order of magnitude larger for background events, giving large improvements in both the available statistics and the signal to background ratio.

The lepton+jets and dilepton decay channels of the $t\bar{t}$ produce high p_t electrons, muons, jets, b-jets, and large missing transverse momentum, exercising the whole detector system. Observation of the $t\bar{t}$ signal in LHC data will be an important milestone in the physics commissioning of the experiments.

Both ATLAS and CMS experiments have prepared multiple top physics analyses and tested them on simulated data in anticipation of the collider turn on. This contribution mentions only a small subset of top physics studies that have been performed.

2. Establishing the signal

The $t\bar{t}$ production cross section has been measured only for the Tevatron energies. Measuring it at the LHC will provide a check on theoretical predictions of the cross section in the new energy regime.

A CMS study [1] demonstrates that $t\bar{t}$ signal can be established in the muon+jets channel with as low as $10\mathrm{pb}^{-1}$ of data. The event selection requires exactly one isolated muon with $p_T > 30$ GeV and $|\eta| < 2.1$, and at least one jet with $E_T > 65$ GeV. For jets with $E_T > 40$ GeV and $|\eta| < 2.4$ the left plot of Figure 1 shows the jet multiplicity distribution. The final $t\bar{t}$ selection is defined by requiring at least 4 jets. The invariant mass of hadronically decaying top quark candidates, which are formed by selecting 3-jet combinations with the highest vector sum of the transverse momentum, is shown in Figure 1 on the right. It has a clear peak near the top quark mass. B-tagging is not used in this study, and no requirement on $\not{E}_T$ is made. That makes this analysis suitable for the very early stage, when these aspects of detector response are not well understood.

An ATLAS study [2] uses dilepton decay channels. The event selection requires two isolated leptons (ee, $e\mu$ or $\mu\mu$), $\not{E}_T > 35$ GeV, the direction of the missing transverse momentum should be non-parallel to the muon, and Z decays are vetoed. The selected events are used to produce a 2-dimensional distribution of $\not{E}_T$ vs the number of jets. The "data" distribution is fit with a linear combination of Monte Carlo templates for signal and background processes. It is found that a 5σ observation of the signal can be made with $10\mathrm{pb}^{-1}$ of integrated luminosity, and with $100\mathrm{pb}^{-1}$ one can expect the following precision on the cross section measurement: $\Delta\sigma/\sigma = (4(\mathrm{stat}) \pm 4(\mathrm{sys}) \pm 2(\mathrm{pdf}) \pm 5(\mathrm{lumi}))\%$ Here systematics from QCD showering, ISR/FSR, jet energy scale, trigger efficiency, electron identification efficiency, lepton fakes, are included in the "(sys)" number, and PDF and luminosity uncertainties are shown separately.

3. Use of top quarks for calibrations

The abundant production of top quarks at the LHC, and well established decay properties make it an excellent tool for calibrating the detectors. The higher multiplicities and transverse momenta of jets in $t\bar{t}$ decays, compared to other Standard Model processes, make the calibration environment more similar to the one expected in many New Physics searches.

The predominant decay mode of the top quark is $t \to Wb$ [3]. One expects to find two b-jets in a $t\bar{t}$ event. A way to extract b-tagging efficiency ϵ_b from data is to count the number of b-tagged jets in a sample of $t\bar{t}$ events, and perform a Poisson likelihood fit to this distribution. An ATLAS study [2] demonstrates that the relative precision of $\pm 2.7\%(\mathrm{stat}) \pm 3.4\%(\mathrm{sys})$ on ϵ_b is achievable with $100\mathrm{pb}^{-1}$ of data, for jets with $E_T > 30$ GeV at the working point $\varepsilon_{b,\mathrm{nominal}} = 0.6$ in the lepton+jets channel. The distribution of the number of b-tagged jets in this study is shown in Figure 2 on the left. Another method for measuring b-tagging efficiency with $t\bar{t}$ events is based on identification of a pure sample of b-jets by reconstructing the $t\bar{t}$ decay topology. Unlike the tag counting method described above, the topological selection method allows to study ϵ_b as a function of b-jet parameters. A CMS study [4] uses a likelihood ratio method to select a sample of b-jets, and takes into account the impurities of the sample. The working point of the tagger is varied in the fit to minimize the combined statistical and systematic uncertainty of the measurement. The study combines lepton+jets and dileptonic $t\bar{t}$ samples for $1\mathrm{fb}^{-1}$ of simulated data. The optimized ϵ_b in the barrel region as function of b-jet E_T is shown in Figure 2 on the right. The expected precision on ϵ_b with $1\mathrm{fb}^{-1}$ of data is $\pm 6\%$(sys+stat) in the barrel region, and $\pm 10\%$(sys+stat) in the endcaps.

The well known mass of the hadronically decaying W in lepton+jets $t\bar{t}$ events can be used to calibrate jet energy scale. An ATLAS study [2] selects events with exactly one isolated lepton $p_T > 20$ GeV, $\not{E}_T > 20$ GeV, at least 4 jets with $E_T > 40$ GeV, and exactly 2 b-tagged jets. All light jet pair combinations are used to produce an invariant mass distribution, which is fitted with a set of template histograms that differ in energy scale and resolution parameters. With $50\mathrm{pb}^{-1}$ of data the expected precision on light jet energy scale is 2%, with systematic uncertainties $< 0.5\%$. With $1\mathrm{fb}^{-1}$ of data a 1% precision should be reachable.

4. Physics studies with top

4.1. Top mass

The mass of the top quark has been determined with a high precision at the Tevatron. The latest result that was shown in this conference [5], $m_t = 172.4 \pm 0.7(\mathrm{stat}) \pm 1.0(\mathrm{sys})$, is systematics dominated. The large statistics of $t\bar{t}$ decays at the LHC allows to use tighter event selection to reduce systematic uncertainties and improve the precision of top mass measurement. The Tevatron measurement used sophisticated multivariate techniques in order to extract maximum information from the limited data set. First measurements of top mass at the LHC will use simple cut based analyses, which may have different systematics, providing a powerful cross check of the result.

An example of such cut based approach using lepton+jets channel is presented by ATLAS in [2]. Figure 3, left, shows the distribution of reconstructed top quark mass obtained with $1\mathrm{fb}^{-1}$ of simulated data, along with a fit function. The extracted top mass (for input $m_{t,\mathrm{true}} = 175$ GeV) is $m_t = 174.6 \pm 0.5(\mathrm{stat}) \pm 0.7/\%(\mathrm{b\text{-}JES}) \pm 0.2/\%(\mathrm{JES}) \pm 0.4(\mathrm{ISR/FSR}) \pm 0.1(\mathrm{b\ fragmentation})$ GeV. With the expected precision on light jet energy scale of 1%, and on b-jet energy scale between 1% and 5%, the precision on top quark mass will be between 1 GeV and 3.5 GeV for $1\mathrm{fb}^{-1}$ of data.

4.2. Single top studies

The sensitivity of single top cross section to beyond the Standard Model processes is studied in [6]. The paper concludes that the Wt production channel is not affected by most New Physics models and can provide a model independent measurement of $|V_{tb}|$, while s- and t-channels receive different contributions from different New Physics

Table I: Expected precision on single top production cross section in different channels.

	method	S/B	$\mathcal{L}$	xsec precision
t-chan	cuts	0.37	1fb^{-1}	$\pm 5\% \pm 45\%$
t-chan	BDT	1.3	1fb^{-1}	$\pm 6\% \pm 22\%$
Wt	BDT	0.35	10fb^{-1}	$\pm 20\%$
s-chan	likelihood	0.19	30fb^{-1}	3σ evidence

models. Measurements of individual s- and t- channel cross sections may provide a handle to determine the kind of New Physics contribution if one is found.

At the LHC, the expected single top channel cross sections are $\sigma_t \approx 250$ pb, $\sigma_{Wt} \approx 66$ pb, and $\sigma_s \approx 11$ pb. Measuring the cross sections is complicated by large backgrounds from $t\bar{t}$ and W+jets processes. Some studies in [2] that use cut-based, boosted decision tree (BDT), and likelihood approaches are summarized in Table I. For example, the BDT analysis in t-channel will allow to measure $|V_{tb}|$ with relative precision $\pm 11\%(\text{stat+sys}) \pm 4\%(\text{theor})$.

4.3. $t\bar{t}$ resonances

The large value of the top mass, which is close to the electroweak symmetry breaking (EWSB) scale, may point to a special role that top quark plays in the symmetry breaking. New resonances or gauge bosons strongly coupled to the top quark, such as in technicolor, topcolor, or other strong EWSB models, or in models with extra dimensions, could be manifest in the invariant mass distribution of top quark pairs.

The experimental challenges are $t\bar{t}$ reconstruction efficiency, which drops as the resonance mass increases because decay products of a boosted top quark start to overlap, and the resolution of the reconstructed $t\bar{t}$ mass. A generic narrow resonance at 700 GeV with $\sigma \times \text{Br}(Z' \rightarrow t\bar{t}) = 11$ pb can be discovered with a 5σ significance after 1fb^{-1} of data taking. The discovery potential for a Kaluza-Klein gluon resonance is shown in Figure 3 on the right. With 1fb^{-1} of data a 1.5 TeV resonance will be discovered with a 5σ significance.

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References

1 CMS Physics Analysis Summary TOP_08_005.

2 ATLAS Collaboration, CERN-OPEN-2008-020, Geneva, 2008, to appear.

3 C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008).

4 S. Lowettea, J. D'Hondt, J. Heyninck, P. Vanlaer, CMS Note 2006/013.

5 E. W. Varnes, Top Physics plenary talk, this volume; Tevatron Electroweak Working Group, CDF Collaboration, D0 Collaboration, arXiv:0808.1089 [hep-ex].

6 T. M. P. Tait and C. P. P. Yuan, Phys. Rev. D **63**, 014018 (2001) [arXiv:hep-ph/0007298].

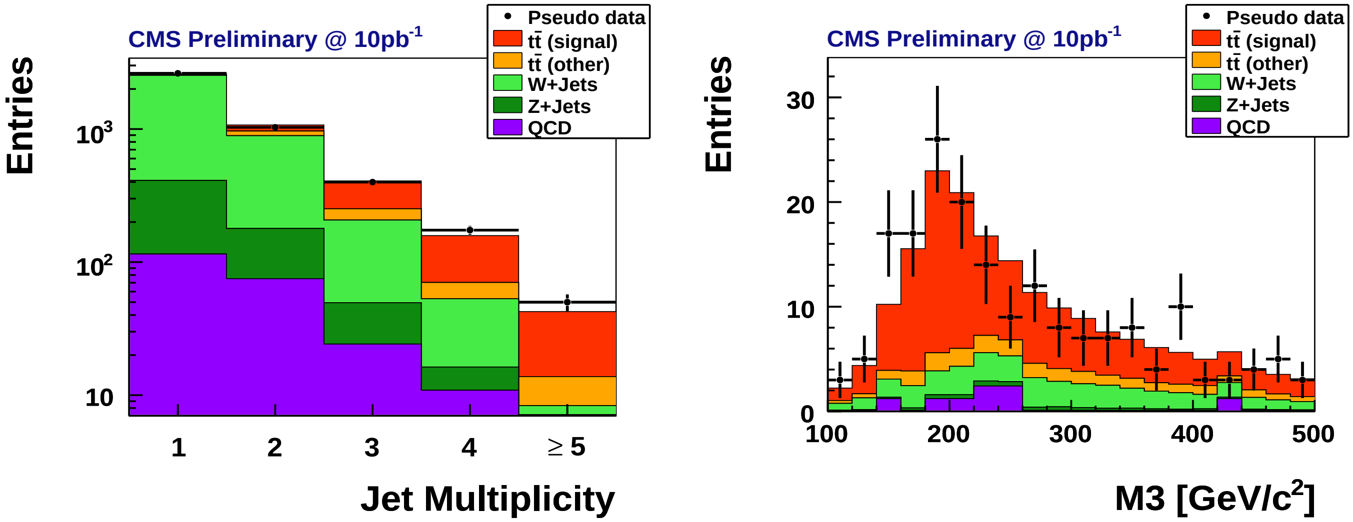

Figure 1: Jet multiplicity distribution (left) and the invariant mass of selected 3-jet combinations (right) in CMS for 10pb^{-1} of simulated data in the muon+jets $t\bar{t}$ analysis.

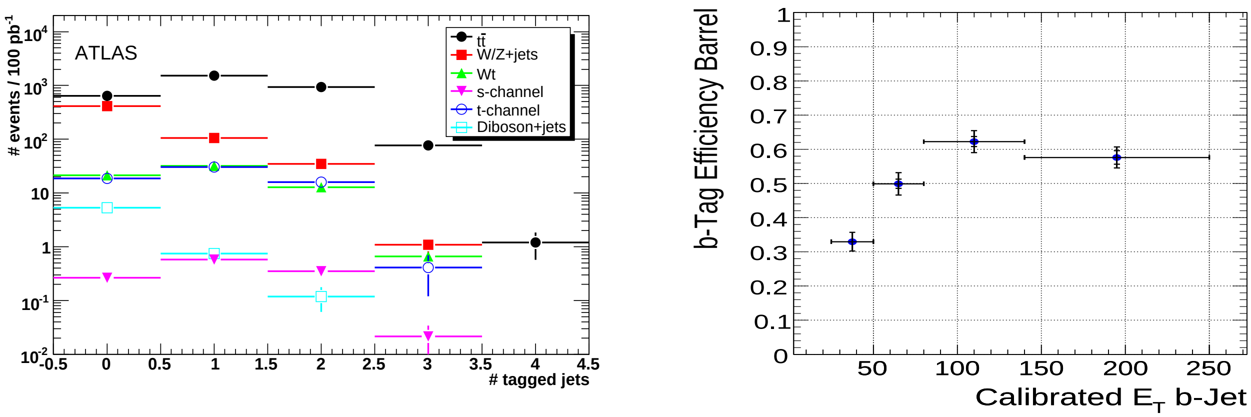

Figure 2: Event yield in lepton+jets channel as function of the number of b-tagged jets in ATLAS for 100pb^{-1} (left). B-tagging efficiency in CMS barrel as function of jet E_T for 1fb^{-1} (right).

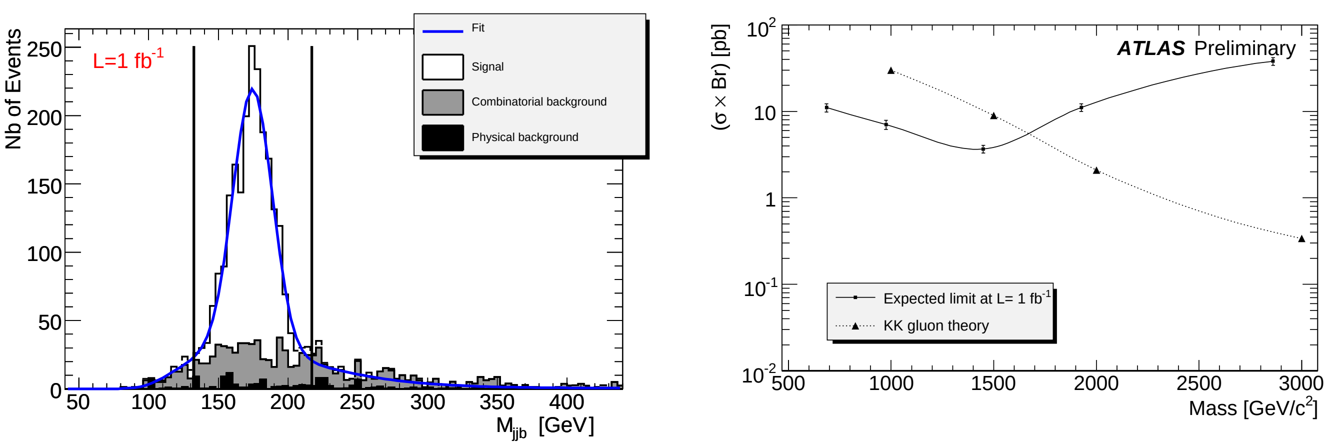

Figure 3: Left: reconstructed mass in the ATLAS cuts based top mass analysis with 1fb^{-1} of simulated data. Right: theoretical cross section of Kaluza-Klein gluon resonance and ATLAS 5σ discovery potential.